

OVERVIEW OF NASA'S ADVANCED PROPULSION CONCEPTS ACTIVITIES

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Abstract

Advanced electric and plasma propulsion research activities are currently underway through the NASA Advanced Space Transportation Program (ASTP) Propulsion Research activity. This research addresses feasibility issues of a wide range of propulsion concepts, and may result in the development of technologies that will enable exciting new missions within our solar system and beyond. Each research activity is described in terms of the present focus and potential future applications. Topics include high power plasma thrusters, electrodynamic tethers, micro-electric thrusters, magnetic nozzle research, fusion propulsion, and advanced electric propulsion mission and systems studies. NASA Office of Space Science missions presently under study and in the agency's roadmap are shown. Advanced electric and plasma propulsion technologies which may enhance or enable this missions are indicated.

Introduction

Something seems to be changing within NASA. At the highest levels within the agency, forward-thinking concepts and risk taking are being not just encouraged, but demanded. Missions are appearing on NASA's science roadmap that cannot be done with existing propulsion technology; some will require impulse bits that are extraordinarily tiny and precise, while others will require spacecraft that will pass by Voyager on their way out of our solar system. Such an environment is exactly what is required to stimulate rapid progress and new ideas in advanced propulsion.

NASA has in place a research program that is focused on evaluating the feasibility of propulsion concepts that offer a significant departure from existing capabilities. The research occurs at several NASA centers, including the George C. Marshall Space Flight Center, the Lewis Research Center, and the Jet Propulsion Laboratory (JPL). Academic institutions such as the University of Michigan, Pennsylvania State University, Ohio State

The research activities described herein are, in some cases, supported by more than one organization within NASA. There is a core budget allocated for the Propulsion Research Program within the Advanced Space Transportation Program (ASTP) by the Office of Aeronautics and Space Transportation Technology (OASTT) at NASA Headquarters. The ASTP is managed at the Marshall Space Flight Center. Since the end of 1997, the Advanced Propulsion Concepts activity at JPL has become a part of the ASTP Propulsion Research Program, resulting in one integrated activity NASA-wide. Last year, total program funding was \$2.55 million. Some of these funds supported advanced propulsion research activities not described herein, such as advanced chemical, nuclear thermal and laser thermal propulsion, and several advanced launch concepts. Of the total budget, \$1.35 million was used to fund advanced electric and plasma propulsion research. Additional support has come from other sources within the ASTP and discretionary grants at individual NASA centers.

For this very modest investment, NASA has undertaken some fascinating research of propulsion technologies that may ultimately lead to accomplishing the most challenging, exciting deep space missions ever attempted. In the following sections, these propulsion technologies which range from the very small and precise to the very large and powerful are described, and some of their potential applications are explored.

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Research Activities

Micropropulsion¹

There currently exists a strong interest within the aerospace community for micropropulsion devices capable of delivering very small thrust values and low impulse bits, and for engine sizes and masses orders of magnitude smaller than are available with current technologies². NASA's interest in these devices results from the drive to explore the feasibility of microspacecraft³, typically viewed as spacecraft having wet masses on the order of 10-20 kg and below, as well as the need for fine attitude control of larger spacecraft like those envisioned for space interferometry missions⁴.

While some micropropulsion devices will be used predominantly in pulsed operational modes for attitude control purposes, others may require a more continuous mode of operation. Two examples for such an application are for high delta-v, primary propulsion on missions to small bodies (comets and asteroids), and for continuous disturbance torque compensation or drag make-up on larger spacecraft.

In cases where spacecraft wet mass has to be kept low, the use of high specific impulse (Isp) propulsion devices may be a necessity to keep required propellant masses small. One approach to high Isp micropropulsion is miniaturization of ion propulsion technology.

The feasibility of reducing ion engine sizes dramatically below state-of-the-art technology^{2,5} to

engine diameters in the 2-3 cm range and thrust levels in the sub-mN range requires an investigation of several key issues. These include the sustainability and efficient operation of high surface-to-volume ratio plasma discharges, the replacement of hollow-cathode technologies with lower-power-consuming and easier to miniaturize cathode systems⁶, the feasibility of fabrication and operation of miniaturized power conditioning units and feed system components⁷, and miniature accelerator grid system fabrication and operation⁵.

At present, there are several micropropulsion research activities underway at NASA's Jet Propulsion Laboratory. These activities include experimental and theoretical studies of cold cathodes⁶, and development and testing of micro-machined ion accelerator grids⁵.

Micro-Electric Thruster Grid Testing

Microfabricated ion accelerator grids are being considered for micro-ion engines due to the unrivaled precision with which these components can be made using MEMS (Microelectromechanical Systems) fabrication techniques. Grid electrodes, which require a multitude of closely spaced apertures within tight tolerances to provide for proper hole alignment and beam extraction, are particularly challenging in view of the small overall dimensions of micro-ion engines. The fabrication of these grids will require the use of new materials not typically used in the fabrication of conventional grids. Specifically, the grid insulator material used to isolate the screen and accelerator grids from each other will have to sustain stand-off voltages on the order of 1.3 kV or more for the thruster to attain a high specific impulse.

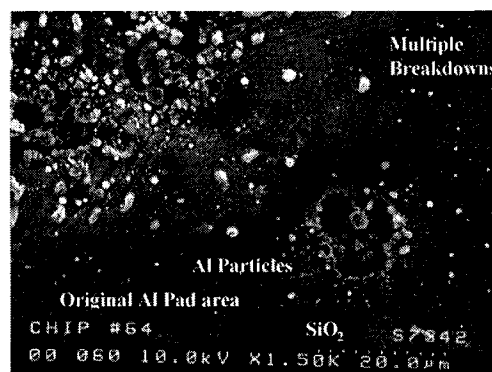
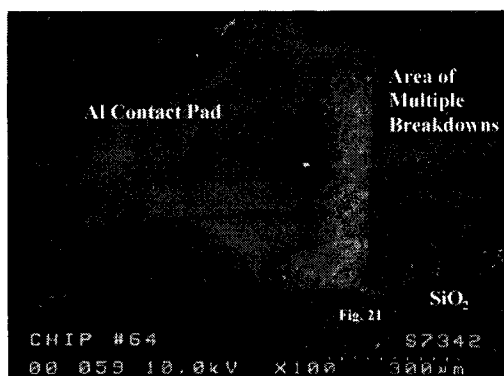


Fig. 1a: Multiple Breakdowns for 1 μm Oxide. Note preferred Breakdown Locations on Aluminum Pad Edge and Corner. 1b: Close-up of same.¹

The present scope of this research is to investigate the feasibility of silicon dioxide as a micro-ion thruster grid insulator material. Silicon dioxide was selected because it exhibits good insulating characteristics and is already widely used in the microfabrication field. Electric breakdown characteristics through the substrate and along its surface are being studied in great detail. Recently, two experiments were conducted using specially designed silicon oxide breakdown test chips to systematically study both modes of electric breakdown. The results showed that although bulk

electric breakdown properties of the oxide are excellent, (voltages as high as 2500 V could be maintained over an oxide thickness of 3.9 μm , providing more than sufficient margins of safety for grid applications), the surface breakdown properties are still inadequate; Although it was discovered that surface breakdown electric field strengths increase significantly with smaller gap distances, reaching a maximum of 140 V/ μm for 5 μm , obtainable voltages over these distances remain relatively small (700 V). Follow-on work will be an investigation of new grid/insulator

geometries, as it was evident from the experiments that the field concentration at these locations plays a major role in oxide breakdowns.

Field Emission Cathodes⁶

While the grid technology represents one key component in a micro-ion engine, another presenting unique feasibility issues is the cathode.

With robust field emitter materials to withstand hostile thruster environments and low operating voltages, a Field Emitter Array (FEA) cathode is a plausible candidate as a low power and efficient electron source for micropropulsion systems.

FEA cathodes typically employ a triode configuration with an emitting cone, gate electrode, and anode that collects the emitted current. Electric fields at the emitting tips in excess of 4×10^7 V/cm are required for field emission. Emission currents greater than 1 μ A/tip can be obtained with operating voltages of less than 100 V. Tip and gate aperture radii are on the order of 1 and 100 nm, respectively. Packing densities can be as high as 1×10^8 tips/cm². Emission current densities greater than 1000 A/cm² have been achieved with small arrays of tips.⁶

FEAs have demonstrated stable emission in elevated pressure environments when start-up occurs at around 1×10^{-9} Torr and an ambient gas is slowly introduced.⁸

Recent work at the University of Michigan and the Jet Propulsion Laboratory has been focused on the key feasibility issue of FEA cathode operation in higher pressure environments. This work includes modeling of field emission array cathode lifetime and emission limitations in electric propulsion systems.

An ultra-high vacuum chamber facility for testing cathodes in varying xenon pressure environments has been set up. This facility is being used to validate the modeling work and to explore possible cathode failure modes.

Also in progress is the fabrication of a micro einzel lens for focusing and decelerating electron beams and repelling ions. Making the multi-electrode micro sandwich has been the recent focus. Once the adhesion of the all of the layers in the structure is adequate, channels will be etched through to the silicon wafers using reactive ion etching.

In addition to micro-ion thruster applications, field emitter arrays may also operate in oxygen environments - a feature making their use with in-situ-produced propellants attractive.⁹ Tests at Linfield Research Institute (LRI) of single ZrC and HfC tips at 1000s of volts showed that emission continued for several minutes at $1 \text{E-}4$ Torr of Ar and O₂. Although a glow discharge operating mode was attained, the tips were not destroyed during operation for a few minutes in this regime. The results of these experiments in elevated pressure environments is very promising,

especially because some of the tips seemed to be undamaged during operation.⁶

Another application of field emitters to propulsion systems is as plasma contactors; such an application may be needed for electrodynamic tethers.

Electrodynamic Tethers¹⁰

Electrodynamic (ED) tethers offer a method of propellant-free propulsion for orbit transfer and power generation in the Earth's magnetosphere. By using the voltage induced in a long conducting tether moving through the Earth's magnetic field and closing the circuit through the surrounding plasma, a drag force is created that can be used to lower a spacecraft orbit and simultaneously generate power. Alternatively, using power applied by a spacecraft to force a current down a tether produces a force in the reboost direction along the orbit. Actual current in a tether is determined by the ability of a tether's plasma contactor to eject electrons, and for a bare conducting tether and endmass to collect electrons. Feasibility studies have also been undertaken to examine the use of electrodynamic tethers in the Jovian magnetosphere.¹¹ Jupiter's rapid rotation produces a condition where a tether can produce power and raise orbit passively and simultaneously at orbits above 2.2 Jupiter radii.

A near term demonstration of ED tether technology is the ProSEDS (Propulsive Small Expendable Deployer System) mission under development at the NASA Marshall Spaceflight center. ProSEDS is an effort to validate bare tether technology in space and demonstrate the use of electrodynamic tether propulsion for the accelerated deorbit of a Delta II second stage. The planned 2000 launch of the ProSEDS flight experiment is a precursor to several applications, including electrodynamic tether upper stages, and International Space Station reboosting.

ProSEDS is a 20 km long tether, 5 km of which is bare aluminum wire. The tether will be released in an upward deployment from a 400 km orbit. Approximately 100 watts is anticipated to recharge batteries for downlink telemetry, along with a 5 to 10 kilometer per day altitude drop of the Delta II upper stage from its initial altitude (See Figure 2).

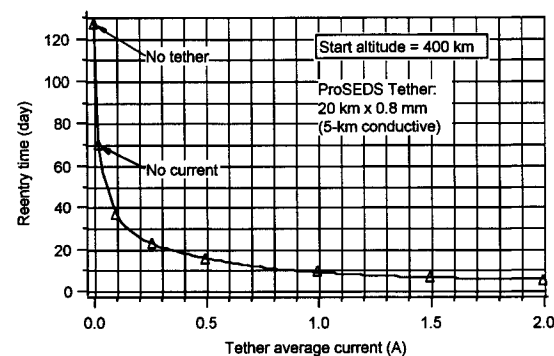


Figure 2. Reentry time of Delta II second stage as a function of tether current. Between 0.5 and 5.0 amperes is expected.¹⁰

The use of electrodynamic tethers for deorbit propulsion would eliminate the need to preserve onboard fuel for deorbit maneuvers at the end of life. As such, there is significant commercial interest in the technology for use on planned telecommunications satellite systems; this application is being explored by Tethers Unlimited under the Small Business Innovative Research Program.

Tether research, as well as many aspects of the micropropulsion studies described earlier, are geared toward reducing or eliminating propellant mass or making systems smaller and lighter. The next topics are a departure from that theme; they pertain to advanced propulsion concepts that hold promise for processing orders of magnitude more power than state-of-the-art propulsion technology, possibly enabling outer-planet sample return missions, and someday perhaps fast interplanetary travel and interstellar precursor missions.

The first of these concepts is the Lorentz Force Accelerator (LFA), also known as the magnetoplasmadynamic thruster. LFA research has spin-off applications that may be used to enhance near-term propulsion technologies, and may also serve to address feasibility issues of other advanced propulsion concepts that are difficult to study in the laboratory.

Lorentz Force Accelerators¹²

The Li-LFA is a steady-state magneto-plasmadynamic thruster (MPDT) that uses a multi-channel cathode and lithium propellant to provide high efficiency and long lifetime previously unattainable with gas-fed MPDTs¹³. A 500-hour lifetime test of a 500-kW Li-LFA at Energiya in Russia¹⁴ has shown negligible erosion and a thrust efficiency of 55% at an I_{sp} of 4500s and a thrust of 12.5N. The demonstrated capability of a single thruster to process MW-level power with a 25N/MW thrust-to-power ratio at high specific impulse renders

the Li-LFA an ideally suited option for heavy cargo and piloted NEP missions for planetary exploration.

In cooperation with JPL, a 30-100 kW level self-field thruster has been developed in collaboration with Thermacore Inc. The thruster, shown schematically in Figure 3, has a novel lithium mass flow rate system that relies on advanced heat pipe technology and calorimetry to allow control of the mass flow rate of lithium vapor (at and above 1000C) without any mechanical or moving parts.

Recent work at Princeton focused on 1) detailed thermal modeling of the device, 2) improvement of the cathode heating scheme and 3) development of specialized diagnostics including multi-color pyrometry, CCD-based emission spectroscopy and a new water-cooled thrust stand for performance characterization in the 100 kW range.

The first firing of this thruster showed that the cathode temperature was not high enough to ensure that only lithium vapor flows through the multi-channel cathode. Consequently a new cathode design was developed at Thermacore and featured eight closed lithium heat pipes along the cathode as shown in Figure 4. The heat pipes conduct heat from a dedicated heater applied on the part of the cathode extending behind the backplate. A series of iterative tests at Princeton produced a technique that relies on a series of radiation shields and a retractable blocking screen to heat the cathode to lithium vapor temperatures (near 800 °C). A detailed 3-D thermal model of the thruster has been developed at Princeton and is being used to study the heat transfer and lithium propellant flow control.

An analytical model for the scaling of thrust in self-field MPDTs was recently developed¹⁵ and will be adapted to the LFA configuration and used to study the thrust scaling of the device. A 2-D numerical MHD code that includes much of the relevant physics is presently being developed.

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are needed to see this picture.

Figure 3: Schematic of Li-LFA showing the open-ended heat pipe which acts as a lithium reservoir at one end and a multi-channel cathode at the other.

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Figure 4: Improved Li-LFA tungsten cathode assembly showing eight closed heat pipes along the cathode for better control of cathode temperature.

The Moscow Aviation Institute (MAI) is also studying the feasibility of high power Li LFA's under a contract with JPL. The research at MAI focuses on the demonstration of high performance at high power and characterization of cathode wear processes. The goal of 50% efficiency at 4000-4500 s Isp was recently achieved in a 200 kWe-class, radiation-cooled thruster. This thruster uses a multi-channel hollow cathode which operates at up to 3000 A. Cathode wear processes were characterized in 100 hours of testing on a 30 kWe device which was scaled to simulate the cathode environment of the higher power thruster. These preliminary data suggest that cathode lifetimes of 100's of hours may be possible with the existing design. Subsequent experiments will study the effect of adding barium to the Li vapor stream, which should significantly extend

cathode lifetime. The programs at MAI, Princeton and JPL are closely coordinated. MAI has built a 30 kWe thruster which will be used at Princeton with a Li feed system built by JPL to verify MAI's thrust measurements and perform more detailed diagnostics of the cathode region. Princeton is building a six-color video pyrometer to be delivered to MAI to determine temperature distributions on the high power thruster cathode. These efforts should ultimately reveal whether this technology can provide adequate performance at the required power levels with sufficient lifetime needed for fast outerplanetary and sample-return missions.

In addition to its study for use as a thruster, the LFA may have interesting spin-off applications to material processing that may benefit other propulsion system; JPL is currently involved in researching the use of an LFA plasma source for chemical vapor deposition of diamond film.

Diamond Film Coatings from CVD Process using a LFA Plasma Source¹⁶

Diamond possesses a combination of properties which makes it uniquely suited to a number of scientific, military, and industrial applications. Work performed at JPL and the California Institute of Technology over the last several years has identified potential benefits diamond-like materials in advanced thrusters. One such application is the use of chemically vapor deposited (CVD) polycrystalline diamond as a coating for ion thruster grids subject to the life-limiting effects of sputter erosion from charge exchange ions. The first phase of this activity was the measurement of the sputter yield of polycrystalline diamond relative to molybdenum and carbon-carbon composite (candidate ion engine grid materials)^{17,18}. Other potential propulsion related applications include coatings for Hall thruster insulators, nozzle throats in chemical rockets, and fabrication of cold cathode field emitters.

One approach to large scale production of chemically vapor deposited diamond is the use of plasma discharges to create the required chemical environment for growth. DC-arcjet sources have been successfully used in the synthesis of diamond and have demonstrated higher rates of deposition than other sources using different gas activation processes. Materials processing with DC-arcjets represents an effective dual use of this technology which has benefited from extensive studies characterizing arcjet thrusters performed over the years. Other electric propulsion technologies may also possess unique advantages for materials processing. Although the LFA may be particularly well suited to diamond synthesis, its potential has not been explored. As of this writing, diamond CVD has been demonstrated in the laboratory in preliminary tests using a LFA plasma source. There have now been two successful growths of continuous polycrystalline diamond film, one of which measured approximately 4.5 microns thick after an hour of run time. Work is currently underway to characterize and model the gas phase chemistry.

While LFAs may find use in materials processing applications as well as enable fast interplanetary missions, they can also serve as a research tool for investigating the interactions of plasma with magnetic nozzles. Such research is directly related fusion propulsion concepts¹⁹.

The next section of this paper describes NASA's present involvement in fusion research for propulsion applications. It also explores the recent thinking at the U.S. Department of Energy which has invested heavily in fusion research for terrestrial power applications over the last few decades.

Fusion Propulsion Research

Magnetic Nozzle Research¹⁹

Exploration of the Solar System would benefit from propulsion systems that have high values of both thrust-to-weight ratio and specific impulse. Heliocentric thrust-to-weight ratios exceeding unity, with specific impulse values in the range of 20,000 - 50,000 sec, could permit efficient performance over nearly straight-line trajectories between planets. For so-called 'advanced-fuel fusion reactors', such as those using D-He³, average particle energies must approach or exceed 100 keV, corresponding to speeds greater than three million meters per second. Direct use of the fusion plasma as the rocket exhaust would represent a specific impulse of about 300,000 sec, far above optimum values for fast interplanetary missions at estimated, maximum values of system specific power. Instead, a portion of the fusion plasma might heat a much larger mass of hydrogen to stagnation temperatures in the range of 80 - 100 eV, resulting in specific impulse values in the optimum range (~30,000 sec). Such temperatures (~ million K) in the stagnation chamber and flow channel greatly exceed values allowed by solid structures, so concepts invoke the use of "magnetic nozzles".

For a magnetic nozzle to channel flow in the manner of a solid nozzle requires currents to circulate around the plasma in a layer at the boundary between the plasma and the solenoidal magnetic field. In this layer, plasma and magnetic flux interpenetrate over a distance that depends on the relative sizes of the resistive skin-depth, mean free paths and radii of gyration of particles in the magnetic field. To free plasma with high electrical conductivity from magnetic flux generally involves dissipation, resulting in the loss of directed kinetic energy. The relative loss of flow kinetic energy should, therefore, depend on the fraction of the plasma flow penetrated by magnetic flux. This fraction scales with the ratio of the thickness of the current layer to the radius of the nozzle. Loss in a magnetic nozzle thus resembles viscous loss in the boundary layer of a conventional, solid nozzle, with the magnetic Reynolds number serving in place of the usual (viscous) Reynolds number for estimating the extent of dissipation.

Under NASA sponsorship, The Ohio State University and Los Alamos National Laboratory have been

collaborating on a program to evaluate magnetic nozzles for advanced propulsion. This collaboration includes comparison of magnetohydrodynamic calculations by Ohio State, using the MACH2 code, with plasma kinetic modeling by Los Alamos, in order to design laboratory experiments that match the physical regime of future propulsion systems. These laboratory experiments will use a gigawatt-level, quasi-steady, magnetoplasmadynamic source, driven by the Godzilla pulser at Ohio State, to emulate the high temperatures of a fusion-reactor heated flow. MACH2 calculations predict specific enthalpies from such a source that correspond to exhaust values of specific impulse exceeding 20,000 sec. Analytical estimates indicate that the relative values of throat radius, resistive skin-depth, mean free paths and gyroradii in the magnetic nozzle channeling the source flow will follow relative values in future rockets at much higher power levels. The gigawatt-level experiments at Ohio State, combined with numerical and analytical modeling, therefore, can provide a useful basis for assessing the viability of a critical element for fusion-powered rocket concepts.

Dense Plasma Focus

The DPF operates in a similar fashion to other MPD devices, with an electrical current flowing between outer and inner concentric cylindrical electrodes. However, in the DPF, the current pinches into a dense, magnetically stabilized configuration termed a "plasmoid". These plasmoids can attain sufficiently high temperatures and densities for fusion reactions to occur.²⁰

Simultaneously, two highly directed beams of ions and electrons are emitted, which potentially allow the efficient use of much of the energy involved in the input pulse as well as in the fusion reactions. Emitted fusion product ions have specific impulse of up to 1.7×10^6 sec. Because a large fraction of the energy can be released in the form of directed kinetic energy suitable for producing thrust, the DPF may be more applicable for propulsion than for other energy applications, which would require highly efficient means of transforming the beam energy into electrical current.

The plasma focus has been the subject of considerable research over the past two decades²¹. However, both the experimental designs and the conceptual propulsion systems are based on purely empirical scaling laws; no satisfactory theory of the operation of the DPF has been widely accepted.

The scope of the work presently underway at Texas A&M University and Lawrenceville plasma physics is to develop a model of the DPF, predict performance using particle-in-cell simulations based on this model, and to compare the results with experiment using an advanced fusion fuel - pB11.

Modeling work thus far has predicted that DPF performance should improve, achieving higher ion

temperatures, when using heavier gases. Earlier experiments at the University of Illinois²⁰ have given preliminary confirmation of this theory by showing successfully predictions of neutron yield from current at the time of pinch for both pure deuterium and d-He⁴ mixtures. With deuterium, fusion yield could be enhanced 5-6 fold by using smaller radius electrodes. With d-He⁴, neutron yields with 10% deuterium a third as high as with 100% deuterium at the same pinch current were achieved. If plasma parameters had not improved as expected, 100 times fewer neutrons would have been recorded with 10% deuterium.

The reaction products of hydrogen fusing with B11 are all alpha particles, hence pB11 is termed an aneutronic fusion fuel. However, some neutrons will be produced from interactions between alpha particles already formed from previous fusions with remaining B11. The experiments, being conducted at Texas A&M University, will seek to detect these neutrons. The peak current sought is 2.6 MA with fill pressure of 4.6 Torr and an operating temperature(which controls the decaborane vapor pressure) of 78°C.

Los Alamos National Laboratory at the Air Force Research Laboratory (at Kirtland Air Force Base) have both contributed equipment for these experiments, including molds for high voltage insulators and capacitors (580 1.86 microfarads cans)

The experiment will use 100 capacitors with a 340kJ maximum energy capacity, but will use around 160-170kJ. The additional capacitors provide the capability to scale up to 2 MJ.

Gasdynamic Mirror²²

The Gasdynamic Mirror fusion concept is one that has been selected by the Marshall Space Flight center for investigation with cooperation from the University of Michigan.

The Gasdynamic Mirror (GDM) is an example of a magnetic confinement fusion propulsion system with a particularly simple design, consisting primarily of a long, slender solenoid. Plasma is trapped within the magnetic fields of a series of toroidal shaped magnets in the central section of the device, while stronger end mirror magnets provide axial confinement (see Figure 5).

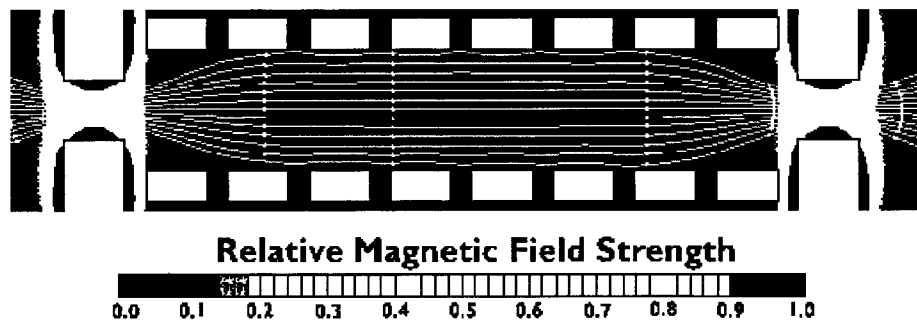


Figure 5. Schematic representation of the gasdynamic mirror configuration.

Large length-to-diameter ratios are sought for the GDM to avoid magnetohydrodynamic (MHD) flute instabilities observed in prior mirror fusion concepts. Loss cone microinstability are predicted²² to not be a problem due to the collisional regime (collision mean free path /plasma mirror ratio << length of the device). The purpose of the present effort is to build a small, subscale device which can be used to study the feasibility issues of plasma stability and confinement associated with this concept, and to map the stability region. The present experiment will be approximately 3 meters long. The configuration of the magnets will be flexible so that it can be rearranged easily to accommodate changing experimental objectives.

Antimatter Initiated Fusion

Since the late 1980's, NASA has sponsored research at the Pennsylvania State University through the Jet

Propulsion Laboratory. Initially, this research was for feasibility studies and systems evaluation of a concept for using antiprotons to "catalyze" a fission/fusion burn of a D-T fuel pellet with a fissionable outer shell. The concept was called ICAN²³ (Ion Compressed ANtimatter catalyzed fission/fusion) and is similar to other inertial confinement fusion scenarios where a fuel pellet is compressed and heated by laser or ion beams. However, with ICAN, annihilation of antiprotons with protons in the fuel pellet nuclei results in additional heating and compression of the target. More recently, another antimatter-initiated fusion concept has been put forth by Penn State called AIM(Antimatter Initiated Microfusion)²⁴, and would not require laser or ion beams for fuel compression; confinement is provided by an electromagnetic trap, and fusion fuel droplets are injected into an antiproton plasma contained within the trap.

In order to pursue studies of these concepts, Penn State has constructed a portable Penning trap so that

antiprotons collected from accelerator facilities such as Fermilab can be transported to other test sites where they can be used to investigate interactions with matter. A first-generation trap has been completed and will be used in experiments at the Air Force SHIVA Star facility in New Mexico to demonstrate antiproton beam delivery to a compressed fuel target. In addition, a second generation penning trap is being designed and constructed at MSFC that will be smaller yet capable of holding one to two orders-of-magnitude more antiprotons than the first trap.

An attractive feature of antimatter initiated fusion research is that it advances efforts to manipulate and utilize antimatter with very small supplies. It may therefore allow study of feasibility issues pertaining to the use of antimatter for pure annihilation rockets, where the thruster exhaust is composed only of the charged pions resulting from annihilation reactions.

Alternative Fusion Concepts

The dense plasma focus, gasdynamic mirror, and antimatter initiated or catalyzed fusion reactions are all termed alternative fusion concepts in that they are a departure from mainstream fusion research sponsored by the U.S. Department of Energy for terrestrial power plant applications. There are indeed a plethora of alternative fusion concepts spanning a wide range of relevant parameter space (see Figure 6), many of which were studied by the DOE before a large program focus was initiated. Many of them can be categorized in terms of the confinement mechanism, as in Table 1 below.

The following text appeared in a document submitted by the Lawrence Livermore National Laboratory to the Headquarters of the Department of Energy in October of 1995 regarding alternative fusion concepts.²⁵

“The appeal of alternatives to the mainline fusion approach is not new. Over the years, many different ideas have been examined both theoretically and

experimentally. While there is no guarantee of ultimate success of any of these alternates, the payoff of a successful alternative could be very high, and therefore warrants a continued and dedicated effort towards their development. *We believe it more likely that an attractive fusion power plant, if there is one (or more), will come from new or revisited physics approaches than from refined engineering for the present path.*”

The document goes on to recommend a National program to study alternative concepts with the following approach:

1. identify/analyze key physics/technology issues for selected concepts,
2. identify next-step experiments to address those issues,
3. study the development pathways needed for the concepts, and
4. evaluate the power plant embodiment of the concepts.

Many in the space propulsion community have long believed that conventional, large scale DOE fusion investments in Tokamak research and laser fusion devices would not greatly benefit propulsion applications because of the implicit large mass and configuration of such systems. NASA has made some effort to identify concepts with attributes which may be particularly well suited for propulsion applications. The rebirth of a serious alternative fusion concepts program may provide a valuable resource for the propulsion community, as there has been an uneven effort to advance various alternative fusion concepts within both NASA and the DOE.

A joint effort with the DOE on the first three of the above four steps may greatly benefit the propulsion community in making headway in the search for one or more viable fusion concepts for propulsion applications; NASA could replace the words “power plant” with “propulsion system” in the fourth step.

LOW DENSITY MAGNETIC CONFINEMENT:

- oStandard field reversed configuration
- oLarge-orbit field reversed configuration
- oSpheromak
- oSpherical tokamak
- oReversed field pinch
- oAdvanced tokamak
- oTokamak
- oStellarator
- oMirror

INERTIAL CONFINEMENT FUSION:

- oConventional IFE (heavy-ion, laser, ...)
- oAdvanced, decoupled-ignition, target systems
- oMagnetized-target IFE
- oHigh yield pulsed systems (batch burn, propagating burn, various ignitors)
- oFission-driven, high yield (PACER, etc.)

HIGH DENSITY MAGNETIC CONFINEMENT:

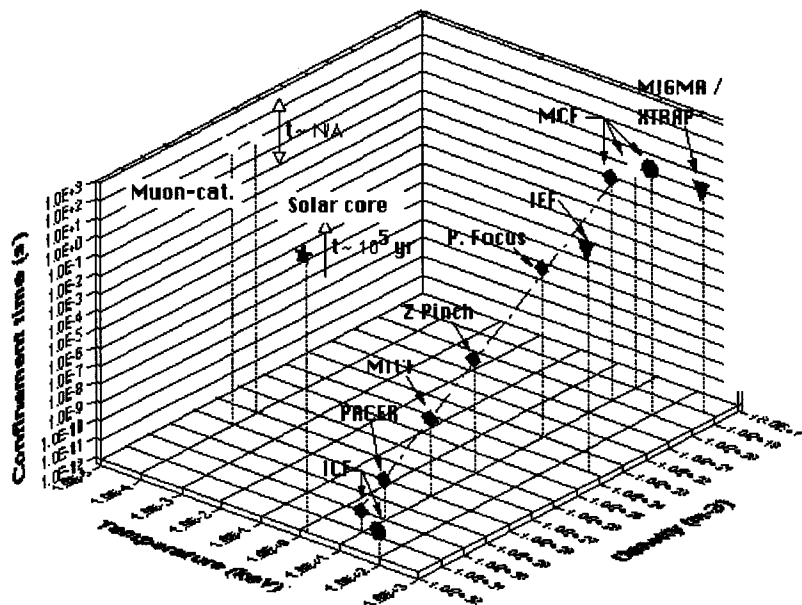
- oPulsed z-pinches (fiber, assisted, z-q pinch, staged,...)
- oPlasma focus
- oContinuous flow pinches
- oWall-confined, magnetically-insulated (various drivers ...)

NON THERMONUCLEAR:

- oInertial electrostatic confinement
- oColliding beam systems (MIGMA, ...)

COULOMB BARRIER REDUCTION SCHEMES:

- oMuon catalysis
- oOthers (Shape-enhanced, antiproton catalysis, ...)

Table I. Classification of alternative fusion concepts.²⁵Figure 6. Parameter space of fusion concepts.²⁵

The fusion research described above is directly applicable to studies of propulsion concepts for interstellar and interstellar precursor mission. The challenge to perform an interstellar mission was posed by the NASA Administrator last year.²⁶

Advanced Electric Propulsion Mission and Systems Studies

Another concept evaluated for interstellar missions was that of using beamed energy to propel a spacecraft by laser photon pressure. In evaluating this concept, the JPL Advanced Propulsion Technology group diverged from the interstellar study to examine the potential relative performance of Laser Electric Propulsion (LEP) to Solar Electric Propulsion (SEP), solar thermal, and laser thermal propulsion for orbit transfer and other example missions.²⁷ The laser electric propulsion concept relies on the use of photovoltaic arrays tuned to operate at highest

efficiency at the frequency of the incident laser beam. Performance projections used in this study were based on experiments performed jointly by JPL and NASA Lewis Research Center to illuminate various solar cells with pulsed laser beams.²⁸

Figures 7 and 8 show the results of this evaluation for two different cases: 1. determining the initial mass in low Earth orbit (IMLEO) for a fixed payload mass,

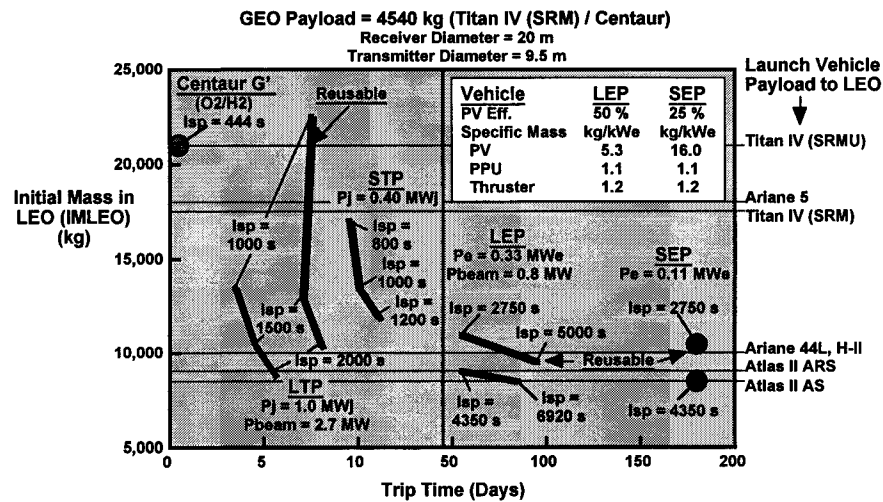


Figure 7. Comparison of chemical, solar thermal, laser thermal, solar electric, and laser electric propulsion for LEO-GEO missions. Case 1: Fix payload mass, determine IMLEO

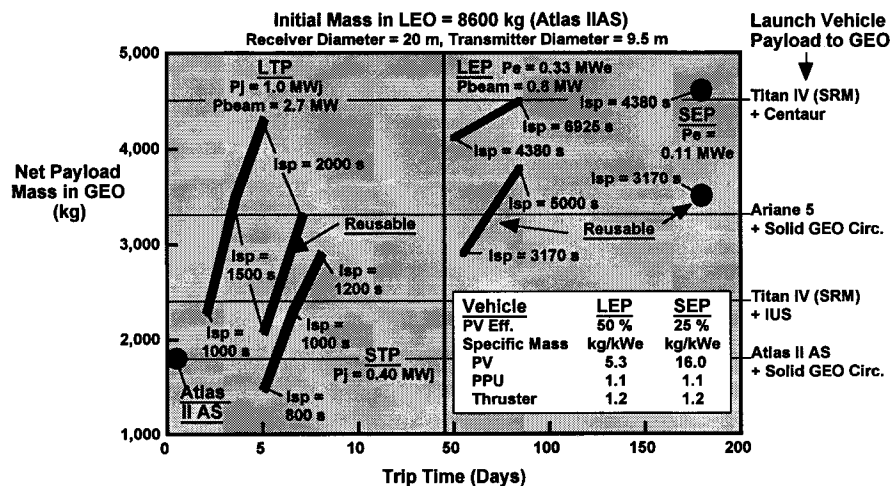


Figure 8. Comparison of chemical, solar thermal, laser thermal, solar electric, and laser electric propulsion for LEO-GEO missions. Case 2: Fix IMLEO mass, determine payload mass

and 2. holding the IMLEO fixed and determining the payload mass. These results indicate that if the infrastructure were in place, both large mass savings, enabling the use of lower-cost launch vehicles, and trip time savings would be possible using laser electric propulsion.

Applications to NASA Space Science Program Objectives

There is an interesting interplay between planning NASA missions and technology availability. To pursue a technology development beyond conceptual stages, a specific desired mission that requires it must first be advocated to provide motivation. Historically, it appears difficult within NASA to obtain support otherwise. In light of this, an examination of the missions currently in the planning stages by the NASA Office of Space Science (OSS) shows that there are many missions that could be significantly enhanced or enabled by advanced propulsion technology. All missions currently in the study phase by the OSS are shown in Table 2.²⁹

There are other mission listed in the roadmap of the Office of Space Science not currently in the mission design and planning phase. Many of these missions related to planetary exploration could also benefit from advanced electric and plasma propulsion technologies, and are listed in Table 3.

| Mission | Goal | Micro propulsion | ED Tethers | EP | Fusion |
|---|---|------------------|------------|----|--------|
| ACCESS | Attached payload on the International Space Station (ISS) slated to replace the Alpha Magnetic Spectrometer (AMS) in 2005. Contain three instruments: Hadron Calorimeter, Transition Radiation Detector (TRD), and the Ultra Heavy/Charge (UHC) Module. | | | | |
| ARISE (Advanced Radio Interferometry between Space and Earth) | Provide a VLBI observing capability at frequencies between 5 and 86 GHz, with space-ground interferometer sensitivity on the order of 50 times better than that for VSOP and RadioAstronomy at the common frequencies. | | | | |
| BOLT (Broadband Observatory for the Localization of Transients) | A Small Explorer mission to determine the origins of gamma-ray bursts. | | | | |
| Constellation (HTXS) | The Constellation X-ray Mission: Next Generation X-ray Observatory dedicated to observations at high spectral resolution, providing as much as a factor of 100 increase in sensitivity over currently planned high | | | | |
| CONTOUR | COMet Nucleus TOUR: A Mission to Study the Diversity of Comet Nuclei. | | | | |
| Deep Space 3 | Formation flying optical interferometer consists of three separated spacecraft forming an equilateral triangle. Provides a technology demonstration for multiple spacecraft precision formation flying and very long baseline optical interferometry. | | | | |
| Deep Space 4 (Champion) | Test advanced technologies for landing on small bodies in the solar system, and for collecting samples of those bodies and return them to Earth. Will launch in 2003 and rendezvous with the periodic Comet Tempel 1 in 2005. | | | | |
| Europa Orbiter | Send a spacecraft to Europa to measure the thickness of the surface ice and to detect an underlying liquid ocean if it exists. | | | | |

Table 2. NASA Office of Space Science missions under study and enhancing or enabling electric and plasma propulsion technologies.

| Mission | Goal | Micro propulsion | ED Tethers | EP | Fusion |
|---|---|------------------|------------|----|--------|
| FIRST (The Far InfraRed and Submillimetre Telescope) | Perform photometry and spectroscopy in the 80-670 μm range. FIRST will study galaxy formation in the early universe, interstellar medium physics star formation - in our own and external galaxies, and cometary and planetary atmospheres. Orbit around L2. | | | | |
| GALEX (The Galaxy Evolution Explorer) | Space ultraviolet small explorer. Will map the global history and probe the causes of star formation over the redshift range $0 < z < 2$, 80% of the life of the Universe, the period over which galaxies have evolved dramatically. | | | | |
| Genesis | Send a spacecraft beyond the influence of Earth to collect pristine material from the solar wind for a period of two years, and then return the samples to | | | | |
| GLAST (Gamma-ray Large Area Space Telescope) | Orbiting telescope for high-energy (10 MeV - 100 GeV) gamma rays. Designed for making observations of celestial gamma-ray sources. The GLAST Mission is under study for flight in the first decade of the next century. | | | | |
| Interstellar Probe | | | | | |
| LISA (Laser Interferometer Space Antenna) | Detect and study low-frequency gravitational waves, with application to astrophysics, cosmology, and fundamental physics. Designed to detect the gravitational radiation from regions of the universe which are strongly relativistic (e.g. near black holes). | | | | |
| Mars Surveyor 2001 | allow scientists to study the ancient climate and geologic history of Mars, investigate the role water may have played on Mars in the past and search for evidence of ancient life. | | | | |
| MUSES-CN | Sample return mission to the asteroid. The target asteroid will be Nereus or 1989ML. Will return fragments of Asteroid's surface to the Earth for detailed analysis. | | | | |
| NGST (Next Generation Space Telescope) | | | | | |
| OWL (Orbiting Wide-angle Light collectors) | An Earth Orbiting Lens to Study Air Showers Initiated by $>10^{20}$ eV Quanta | | | | |
| Planck | Designed to image the anisotropies of the Cosmic Background Radiation Field over the whole sky, with unprecedented sensitivity and angular resolution. Will provide a major source of information relevant to testing theories of the early universe. | | | | |
| Pluto/Kuiper Express | Explore Pluto/Charon and the fringes of our Solar System. | | | | |
| Rosetta | Rendezvous with comet Wirtanen and orbit it, while taking scientific measurements. A Surface Science Package (SSP) will be landed on the comet surface to take in-situ measurements. Launched in the year 2003. | | | | |
| SIM | Optical interferometer operating in Earth Orbit (near polar, circular, Sun-synchronous) circa 2004. Will study dynamics of star and star clusters in our Galaxy, using precision global astrometry | | | | |
| Solar-B | Coordinated set of optical, EUV and X-ray instruments that will apply a systems approach to the interaction between the Sun's magnetic field and its ionized atmosphere. Polar, Sun synchronous orbit. | | | | |
| Solar Probe | | | | | |
| STEREO | Provide a totally new perspective on solar eruptions and their consequences for Earth. One spacecraft will lead Earth in its orbit, and one will be lagging; combine simultaneous telescope images | | | | |
| TPF (The Terrestrial Planet Finder) | Infrared interferometer operating in an orbit designed to detect planets and planetary atmosphere constituents that fall into the category of "earth-like." Will search out planetary systems around the brightest 1000 stars within 13 Pc. Possible 3-5 AU. | | | | |

Table 2(continued). NASA Office of Space Science missions under study and enhancing or enabling electric and plasma propulsion technologies.

| Space Science Campaigns | Micro propulsion | ED Tethers | EP | Fusion |
|--|---------------------|------------|----|--------|
| Exploration of the Solar System | | | | |
| Building Blocks and Our Chemical Origins | | | | |
| Pluto/Kuiper Express | | | | |
| Primitive Body Explorers (Multi-Body Visitor Missions) | | | | |
| Comet and Asteroid Sample Returns | | | | |
| Giant Planet Deep Probes | | | | |
| Formation and Dynamics of Earth-Like Planets | | | | |
| Mercury Orbiter | | | | |
| Io Volcano Observer | | | | |
| Mars Seismic Network | | | | |
| Pre-Biotic Chemistry in the Outer Solar System | | | | |
| Europa Ocean Explorer | | | | |
| Europa Landers | | | | |
| Titan Explorers | | | | |
| Astrophysical Analogs in the Solar System | | | | |
| Neptune Orbiter | | | | |
| Uranus Orbiter | | | | |
| Saturn Ring Explorer | | | | |
| Jupiter Polar Orbiter | | | | |
| Mercury Orbiter | | | | |
| The Sun-Earth Connection | | | | |
| Inner and Outer Frontiers | | | | |
| • Solar Wind Sentinels | | | | |
| • Interstellar Probe | | | | |
| Earth's Space Environment | | | | |
| Global Electrodynamics | | | | |
| Comparative Planetary Space Environments | | | | |
| • Mercury Orbiter | | | | |
| • Jupiter Polar Orbiter | | | | |

Table 3. Space Science mission on the NASA roadmap that could be enhanced or enabled by advanced electric and plasma propulsion technology.

Concluding Remarks

Advanced electric and plasma propulsion research activities are currently underway at NASA. These studies address the feasibility issues of a wide range of propulsion concepts, including high power plasma thrusters, electrodynamic tethers, micro-electric thrusters, and fusion propulsion. Such research may result in the development of technologies that will enable exciting new missions within our solar system and beyond.

For example, as primary propulsion, microthrusters may be enabling for fleets of microspacecraft designed for three-dimensional mapping of magnetic fields and

particle distributions, or for performing global survey's of planets. Such fleets would be appropriate for "high risk" missions like a Saturn ring explorer, where loss of a single spacecraft does not impact the overall science return. For fine pointing and attitude control, micropropulsion will have to meet extremely demanding specifications to enable various interferometry missions.

High power plasma and fusion thrusters will be necessary to conduct fast outer planet missions, human exploration of deep space, and interstellar precursor missions. The present emphasis at NASA for investigating the possibility of an interstellar mission is

exemplary of the need for research of advanced plasma thrusters.

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